METHOD OF MAKING BULK INGAN SUBSTRATES AND DEVICES THEREON

CROSS-REFERENCES TO RELATED APPLICATIONS

This Non-Provisional patent application is based on and claims priority to Provisional Patent Application No. 61/392,565, titled METHOD OF MAKING BULK InGaN SUBSTRATES AND DEVICES THEREON, filed on Oct. 13, 2010. This provisional application is incorporated herein by reference for all purposes.

BACKGROUND OF THE INVENTION

The present invention relates generally to techniques using bulk gallium and nitrogen containing substrates. More particularly, the present invention provides a method and device using bulk gallium and nitrogen containing substrates configured in a semi-polar orientation. Merely by way of example, the invention has been applied to use bulk GaN substrates to form overlying epitaxial regions in a bi-axially relaxed state, but it would be recognized that the invention has a broader range of applicability.

Today's state-of-the-art visible-spectrum light-emitting diodes (LEDs) and laser diodes (LDs) in the ultraviolet to green (380-550 nm) regime are based on InGaN active layers grown pseudomorphic to wurtzite GaN. This is true whether the growth substrate is GaN itself, or a foreign substrate such as sapphire or SiC, since in the latter cases GaN-based nucleation layers are employed. To our knowledge, successful demonstration of InGaN-based nucleation layers has not been achieved, and may not be possible given the growth morphology evolution of low-temperature InGaN layers on foreign substrates. FIG. **1** illustrates the energy bandgap vs. basal-plane (a) lattice constant for a Wurtzite (Al, In, Ga)N system, with regions indicated for visible spectrum emission based on both strained-to-GaN and relaxed, InGaN. Reference number **110** represents the basal plane lattice constant for pseudomorphic $In_xGa_{1-x}N$/GAN, and **120** represents the basal plane lattice constant for relaxed $In_xGa_{1-x}N$.

The resulting built-in stress within the InGaN active layers can be problematic for achieving high quality material and good device operation as the InN mole fraction increases, a requirement for longer wavelength devices. For c-plane grown devices, increasing InN increases the built-in electric fields across the active layers due to spontaneous and piezoelectric polarization fields, reducing the overlap between electrons and holes and decreasing radiative efficiency. Moreover, there is evidence for material breakdown as the stress level becomes too high, resulting in so-called "phase separation," beyond a critical limit of a certain InN mole fraction combined with a certain layer thickness. See, e.g. N. A. El-Masry, E. L. Piner, S. X. Liu, and S. M. Bedair, "Phase separation in InGaN grown by metalorganic chemical vapor deposition," Appl. Phys. Lett., vol. 72, pp. 40-42, 1998. Such a limit is observed for InGaN layers of about 10% InN grown more than 0.2 um thick, for example, resulting in "black" or "grey" wafers.

Non-polar (1-100), (11-20), and semi-polar planes of GaN can address some of the problems above. In particular, for certain growth planes the combined spontaneous and piezoelectric polarization vector can be reduced to zero or near-zero, eliminating the electron-hole overlap problem prevalent in c-plane-based devices. Also, improved material quality with increased InN can be observed, such as demonstrated for semi-polar material which has resulted in continuous-wave

(CW) true-green LDs for the first time. See, e.g. Y. Enya et al., "531 nm green lasing of InGaN based laser diodes on semi-polar {20-21} free-standing GaN substrates," Appl. Phys. Express 2, 082101, 2009 and J. W. Raring et al., "High-power high-efficiency continuous-wave InGaN laser diodes in the violet, blue, and green wavelength regimes," SPIE Photonics West 7602-43, 2010. The performance of longer-wavelength devices grown on these structures, however, still suffers considerably compared to that of shorter-wavelength counterparts. In addition, it is not clear that these growth plane orientations would eliminate the materials quality problems associated with strain. Recent characterization of semi-polar (Al,In,Ga)N heterostructures reveals the formation of a large density of misfit dislocations at heterointerfaces between AlGaN and GaN. See, for example, A. Tyagi et al., "Partial strain relaxation via misfit dislocation generation at heterointerfaces in (Al,In)GaN epitaxial layers grown on semipolar (11-22) GaN free standing substrates," Appl. Phys. Lett. 95, 251905, 2009. These dislocations may act as non-radiative recombination centers as well as potential degradation mechanisms which may prevent long-life operation necessary for applications such as solid-state lighting. Finally, the best-reported external quantum efficiencies versus wavelength for LEDs show a strong reduction with increasing InN mole fraction, regardless of growth plane orientation, as illustrated by FIG. **2**. FIG. **2** illustrates external quantum efficiency vs. peak emission wavelength for visible-spectrum light-emitting diodes (After S. Denbaars, DOE SSL Workshop presentation, February 2010). Reference number **210** is an efficiency curve for $In_xGa_{1-x}N$ LEDs grown on a c-plane substrate. Reference number **220** is an efficiency curve representing $(Al_xGa_{1-x})_{.52}In_{.48}P$ LEDs. Reference number **230** represents the efficiency of LEDs (nonpolar substrate), and reference numbers **232**, **234**, **236**, and **238** each represents the efficiency of $In_xGa_{1-x}N$ LEDs (semipolar substrates). Reference number **240** is an efficient curve for LEDs fabricated by UCSB.

BRIEF SUMMARY

According to the present invention, techniques related generally to using bulk gallium and nitrogen containing substrates are provided. More particularly, the present invention provides a method and device using bulk gallium and nitrogen containing substrates configured in a semi-polar orientation. Merely by way of example, the invention has been applied to use bulk GaN substrates to form overlying epitaxial regions in a bi-axially relaxed state, but it would be recognized that the invention has a broader range of applicability.

In this invention we activate the (0001)/1/3<11-20> slip planes in GaN by using semi-polar oriented material and controlled stress at heterointerfaces to form a relaxed InGaN layer which will become a seed for growth of a relaxed InGaN substrate or layer. In one embodiment, a GaN growth surface of a predetermined growth plane (other than c-plane) is provided. This may be accomplished by growing thick c-oriented boules of GaN by techniques such as hydride vapor-phase epitaxy (HVPE) and cutting these boules along predetermined orientations to provide a semi-polar GaN growth surfaces. Next, an InGaN seed layer of a specified InN mole fraction is grown upon the GaN layer by a desired technique such as metal-organic chemical vapor deposition (MOCVD), ammonothermal growth, molecular beam epitaxy (MBE), HVPE, or other methods. The predetermined growth plane combined with stress at the InGaN/GaN heterointerface results in the formation of a network of dislocations which allows the InGaN seed layer to relax. Continued growth of